Magnetotransport in quantum cascade detectors: analyzing the current under illumination

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Magnetotransport in quantum cascade detectors : analyzing the current under illumination

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Photocurrent measurements have been performed on a quantum cascade detector structure under strong magnetic field applied parallel to the growth axis. The photocurrent shows oscillations as a function of B. In order to describe that behavior, we have developed a rate equation model. The interpretation of the experimental data supports the idea that an elastic scattering contribution plays a central role in the behavior of those structures. We present a calculation of electron lifetime versus magnetic field which suggests that impurities scattering in the active region is the limiting factor. These experiments lead to a better understanding of these complex structures and give key parameters to optimize them further.

The quantum cascade detector [1] (QCD) recently proposed and realized in both the mid-infrared [2] and in the THz [3, 4] range is a photovoltaic version of the quantum well infrared photodetector (QWIP) [5]. Their band structure are designed as quantum cascade laser (QCL) without any applied bias voltage [1, 3]. QCD are totally passive systems and show a response only to photon excitation. As such, the QCD structure is designed to generate an electronic displacement under illumination through a cascade of quantum levels without the need of an applied bias voltage.

In a semiconductor quantum well structure, magnetic field applied along the growth direction breaks the 2D in-plane continuum into discrete Landau levels (LLs). This experimental technique has been used to evaluate the different contributions of scattering mechanism in complex quantum cascade structures [5–9].

We present in this paper experimental photocurrent measurements under magnetic field applied along growth direction. We develop a simple model of transport under illumination in a QCD. Through a comparison between experimental and calculation results, we evidence the mechanism limiting the response of the QCD.

The QCD under study is a GaAs/$Al_{0.34}Ga_{0.66}As$ heterostructure with a detection wavelength of 8 μm as described in ref. [9]. It consists of 40 identical periods of 7 coupled GaAs quantum wells. Figure 1 recalls the principle of the device.

QCDs are mounted inside an insert at the centre of a superconducting coil where a magnetic field B up to 16 T can be applied parallel to the growth axis. Light is emitted by a globar source from a FTIR spectrometer and guided to the sample. The experiment consists in measuring the current under illumination (I_{light}) without any applied voltage at 80 K while the magnetic field is swept from zero to 16 T.

Experimental result is illustrated on figure 2(a). The photocurrent shows oscillations as a function of the magnetic field, superimposed on a continous decreasing background which is removed of the experimental data in figure 2(b). Minima of current are located at $B = 10.1$ T, 11.4 T, 13.0 T and 15.3 T

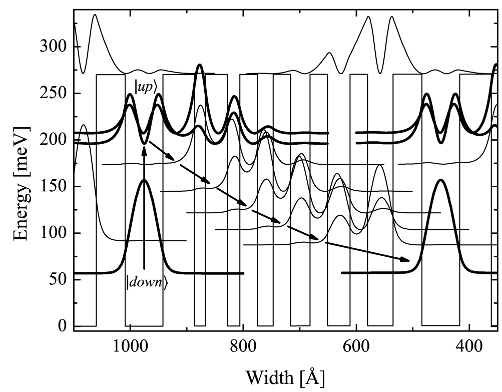

FIGURE 1: Conduction band diagram of one period of an 8 μm QCD showing the energy levels. Note that the ground state of the first QW belongs to the former period and is noted $|down\rangle$. The arrows illustrate the electronic path during a detection event. The layer sequence is as follows 67.8 / **56.5** / 19.8 / **39.6** / 22.6 / **31.1** / 28.3 / **31.1** / 33.9 / **31.1** / 39.6 / **31.1** / 45.2 / **50.8** (the barriers are represented in bold types). The n-doping of the large QW is 5×10^{11} cm^{-2}.

and are in agreement with crossing of LL $|up, 0\rangle$ with LLs $|down, p\rangle$ represented on figure 2(c). It leads to the conclusion an elastic scattering mechanism is dominant in this structure and mainly involves $|up\rangle$ and $|down\rangle$ levels.

We propose a model of transport in one period based on a rate equation approach. We assume that electrons are in the upper detector state $|up\rangle$ through absorption of a photon. Current as a function of lifetimes involved in this structure can be written :

$$\frac{J}{q} = \alpha N_{down} \left(\frac{\tau_{up-down}}{\tau_{up-down} + \tau_{up-c}} \right) = \alpha N_{down} QE \ . \quad (1)$$

The parameters α and N_{down} are respectively the absorption factor and sheet density of $|down\rangle$ and are constant. The subscribe c stands for the whole cascade.

We present in table I the calculated scattering rates of the different processes at $B = 0$ T. For interface roughness, we used a Gaussian autocorrelation of the roughness, with an

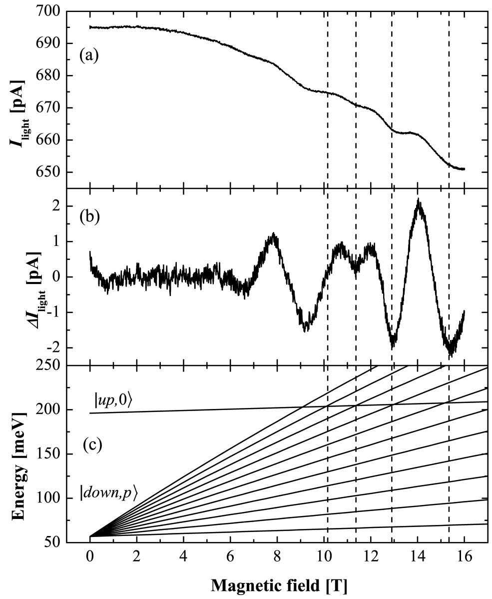

FIGURE 2: (a) Current under illumination as a function of B at 80K and at zero bias. (b) I_{light} as a function of B where the decreasing backgroung as been substracted. (c) Fan chart of $|up, 0\rangle$ and $|down, p\rangle$ as a function of B taking into account the band nonparabolicity.

Scattering mechanism	$1/\tau_{up-down}$	$1/\tau_{up-c}$
LO phonon emission	7.0×10^{11}	7.2×10^{11}
Interface roughness	6.0×10^{11}	8.6×10^{12}
Impurity scattering	1.8×10^{13}	5.2×10^{13}

TABLE I: Scattering rates in s^{-1} are calculated using different scattering processes for an electron in the $|up\rangle$ subband at $B = 0$ T.

average height of $\Delta = 2.8$ Å and a correlation length of $\Lambda = 60$ Å. LO phonon emission scattering rate has been calculated as in ref. [10]. In our structure impurities scattering is the most efficient process [11]. Usually in GaAs quantum cascade structures this mechanism is neglected because the doped layers are not in the active region. In order to take into account the main scattering process we calculate ionized-impurities scattering as a function of magnetic field. The details of the calculation are presented elsewhere [12].

Figure 3 represents a comparison between experimental data and electron-ionized impurities scattering time as a function of magnetic field. Figure 3(b) and 3(c) show the two lifetimes involved in Eq. 1 as a function of B calculated with electron-ionized impurities scattering. Figure 3(d) shows the calculation of the related quantum efficiency.

The oscillating behavior at high magnetic field ($B > 9$ T) is a result of the electronic transfer from $|up\rangle$ to $|down\rangle$. This transfer leads to minima in the current which fit well with $\tau^{\text{imp}}_{up-down}$ and QE. The long period oscillating behavior of τ^{imp}_{up-c} as a function of B enhances the peak at $B = 14$ T in QE in agreement with experimental data. QE, which describes the performance of the detector, is oscillating between

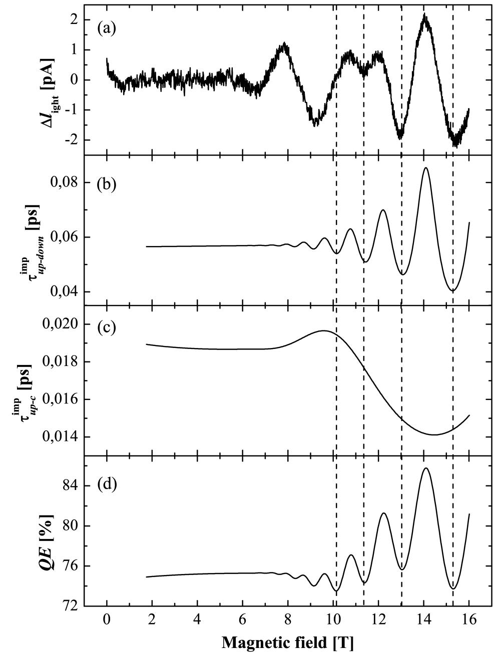

FIGURE 3: (a) I_{light} as a function of the magnetic field where the backgroung has been substracted. (b) Ionized impurity scattering $\tau^{\text{imp}}_{up-down}$ under magnetic field between $|up\rangle$ and $|down\rangle$ levels. (c) Ionized impurity sattering τ^{imp}_{up-c} under magnetic field between $|up\rangle$ and levels in the cascade. (d) Quantum efficiency (QE) calculated with Eq. 1.

74% and 85% under B. By extrapolating, at $B = 0$ T, QE is equal to 75%, a value that should be increased to improve the detector performance. An optimized structure should take these results into account by shifting the ionized impurities from the active region, where they are enhancing $\tau^{\text{imp}}_{up-down}$, to a position where they would only enhance τ^{imp}_{up-c}. The series of peak at $B < 9$ T corresponds to a characteristic energy of 40 meV. This energy is attributed to transitions in the cascade involving an elastic scattering mechanism.

In conclusion, we observe oscillations of the photocurrent in a mid infrared QCD as a function of B. These socillations are due to electron-ionized impurities scattering. This mechanism is dominant in this structure because impurities are located in the active region. In order to improve further this efficiency, we suggest to shift the impurities in another location of the structure in order to minimize $\tau^{\text{imp}}_{up-down}$.

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